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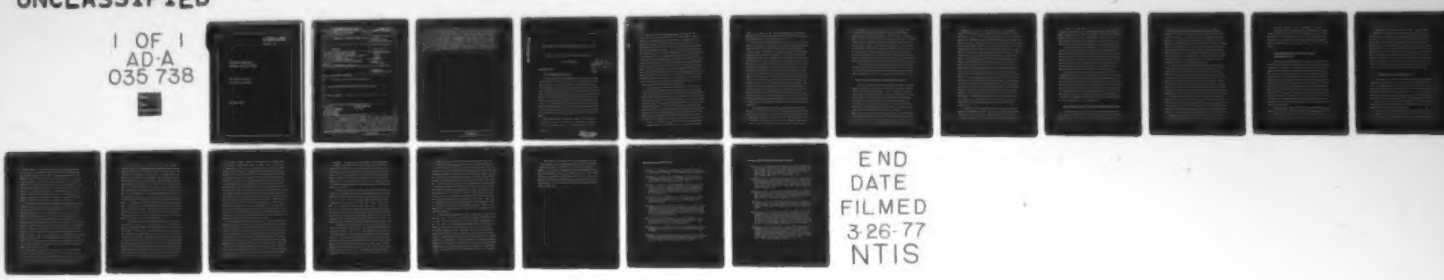

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# FINE SCALE STRUCTURE OF TURBULENT VELOCITY FIELDS

CALIFORNIA UNIVERSITY
SAN DIEGO, CALIFORNIA

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An experimental investigation of three turbulent shear flows-a two-dimensional mixing layer, a high Reynolds number axisymmetric jet, and a cylinder wake-was completed. The measurements provide new information on the higher-order statistical characteristics of these flow fields and on the development of the mixing layer flow towards a self-preserving state. The relevance of initial conditions on the development of the mixing layer flow is considered in light of both present and previous data. Measurements of spectra to fourth order, probability densities and moments to eighth order of all three velocity-component fluctuations

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and their derivatives were performed. An investigation of the validity of the Kolmogorov local similarity theories for the fine scale structure of turbulent velocity fields was undertaken. Studies of several flow fields provide considerable evidence for the existence of universal spectral shapes which are functions of turbulence Reynolds number. The importance of considering effects on spectra caused by deviations from Taylor's hypothesis in high intensity flows was demonstrated. High quality data at large turbulence Reynolds numbers was obtained from an atmospheric boundary layer experiment. Also, valuable data to test the dissipation techniques for estimating the turbulent fluxes of momentum, heat, and water vapor was obtained. Finally an experimental study of the relaminarization of turbulent pipe flow subjected to a large decrease in Reynolds number was initiated.

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# FINAL SCIENTIFIC REPORT FOR GRANT AFOSR 72-2287

## Fine Scale Structure of Turbulent Velocity Fields

F. H. Champagne



## 1. Review of Results

### A. Free Turbulent Shear Flows

An experimental investigation of three different shear flows - a two-dimensional turbulent mixing layer, a high Reynolds number axisymmetric jet, and a two-dimensional turbulent wake from a circular cylinder - was completed. Measurements of spectra to fourth order, probability densities and moments to eighth order of all three velocity component fluctuations at various transverse positions across the flow were carried out using an on-line digital data acquisition system. The probability density distributions of the derivative and the derivative squared of the longitudinal and lateral velocity fluctuations were also determined. The objectives of this study were to provide significant information on the basic structure of these flows and on the higher order statistical characteristics of these free shear flows.

The results of the investigation of the two-dimensional incompressible mixing layer are presented in Champagne, Wygnanski, and Pao (1976) (see publications list). The measurements provide new

information on the development of the mean and turbulent fields towards a self-preserving state as well as on the higher-order statistical properties of the turbulent field. Perhaps the most significant finding was the relevance of initial conditions in the development of the flow field. Previous observations indicated that for the same Reynolds number, $Re_x$, two different growth rates were possible depending on the initial condition of the boundary layer on the splitter plate. A reasonable speculation based on all the available data is that the spread or width of the mixing layer as well as the magnitude of the peak in the intensity profile is proportional to the disturbance level of the initial boundary layer on the splitter plate. One might rightfully ask in view of these results whether in the two-dimensional mixing layer there exists <u>universal</u> self-preserving distributions of the mean velocity, turbulence intensities and other mean quantities not determined by viscous effects. According to the principle of Reynolds number similarity/independence, these self-preserving functions should be universal.

In reply, two alternatives were presented. One is that no universal self-preserving form exists although each mixing layer in itself is self-preserving, the self-preserving functions being dependent on the initial conditions of the flow. Recent flow visualization studies carried out at other laboratories indicate that a vortex-pairing process governs the growth of a mixing layer developing from an undisturbed initial boundary layer. Vortex pairing implies a kind of orderly structure in the flow and perhaps this model is applicable to untripped mixing layers. A reasonable conjecture would be that if the initial boundary layer is highly disturbed or even turbulent the orderly pairing process might occur randomly, in some intermittent fashion, or not at all. Then the pairing process would not govern the growth of the mixing layer and a different growth rate would undoubtedly be

observed. In any case, the initial conditions of the boundary layer plays a strong role in the development of the flow perhaps through the modification of some orderly process.

The second alternative presented was that it is not the initial conditions which are so important, but rather the boundary conditions. This alternative was suggested by Laufer and Browand (private communication). They were concerned primarily with the boundary conditions imposed by the end plates. It is difficult to assess the validity of this alternative, although it was pointed out that a previous investigator used a 50% larger end-plate separation than was used in the present experiments and the results agreed quite well. The need for systematic experiments to investigate the importance of initial conditions and end-plate separation at high Reynolds number (i.e. $Re_x \approx 10^6$) was pointed out. This led to several subsequent experiments at other laboratories, including those at Tel-Aviv University, USC, and Cal Tech. The preliminary findings thus far verify the importance of the initial conditions on the flow development. The mixing layer with a trip wire grows more slowly than that from an undisturbed flow in the first 500 or more momentum thicknesses. Beyond this region apparently the growth rate of the tripped mixing layer approaches that of the untripped case. Results from the studies at these laboratories should provide a definitive basis for an answer to the question on the existence of Reynolds number similarity on the mixing layer.

The measurements of spectra, probability densities and moments to eighth order of all three velocity component fluctuations at various transverse positions across the flow are also presented in Champagne, Wygnanski, and Pao (1976). The probability density distributions of the derivative and derivative squared of the longitudinal and lateral velocity fluctuations were carried out and presented.

Direct measurements of moments to eighth order of the velocity derivatives were attempted and are discussed in light of the simultaneously measured histograms. The problems in obtaining higher-order statistical data are considered in some detail. Estimates of the integral time scales of many of the higher order statistics are presented. Higher-order spectra to fourth order of the longitudinal velocity fluctuations were measured and are discussed. Finally the lognormality of the squared longitudinal and lateral velocity derivative fluctuations was investigated and the universal lognormality of the squared longitudinal and lateral velocity derivative fluctuations was investigated and the universal lognormal constant $\mu$ was evaluated.

The two-dimensional turbulent cylinder wake and the high Reynolds number axisymmetric jet data obtained with the on-line digital data acquisition system was analyzed and the results provide a basis for the study of the high wavenumber structure of turbulent velocity fields.

## B. The Fine Scale Structure of Turbulent Velocity Fields

In the last fifteen years a number of workers have attempted to measure the full one-dimensional spectra of the velocity component fluctuations in many turbulent shear flows. Significant questions regarding the small scale structure of turbulent velocity fields still remain however. In particular, the validity and/or limitations of the original Kolmogorov local similarity theory and the later reformations are still under investigation. Recent studies at this laboratory on universal similarity of the fine scale structure of the velocity field for many different turbulent flow fields, i.e., an axisymmetric jet, a cylinder wake, a mixing layer, the atmospheric boundary layer over land and ocean, and several grid flows provide considerable evidence for the existence of universal spectral shapes which are functions of turbulence Reynolds number. High quality

spectral data was required for this study as the second and fourth moments of the spectra were required out to a Kolmogorov normalized wavenumber of unity. The data considered in this study were obtained from many investigators as well as the present jet, mixing layer, and cylinder wake data. Much of the data was eliminated from consideration based upon inadequate spatial resolution of velocity sensors, insufficient sampling time to determine stable statistical estimates, and inadequate signal-to-noise ratios in the high frequency band of interest. Also revealed was the importance of considering effects on measured spectra caused by deviations from Taylor's approximation in high intensity turbulent flows such as jets, mixing layers, and the atmospheric boundary layer over land. Taylor's "frozen flow" approximation, commonly used to transform temporal fluctuations to convected streamwise spatial ones, is not valid in such flows. Lumley (Physics of Fluids 8, 1056 (1965)) developed a comprehensive model to correct the high frequency portion of a spectrum for effects caused by deviations from Taylor's approximation. The model leads to a differential equation relating the measured and "true" spectra. An analytical solution to the differential equation was obtained which yields the "true" or corrected spectrum in terms of the measured spectrum. The analytical solution was applied to the present jet, mixing layer, and atmospheric boundary layer spectra data and the corrected spectra were obtained. The corrections proved to be significant in searching for universal spectral shapes at high wavenumbers.

Geophysical flows provide the largest turbulence Reynolds numbers and Kolmogorov length scales, but data of sufficient quality from these flows was and still is extremely limited. Thus an atmospheric boundary layer experiment to obtain high quality data on the fine scale structure of the turbulent velocity and temperature fields

was carried out in cooperation with the Air Force Cambridge Research Laboratories (AFSC) in 1973. The experiment was performed at their completely instrumented and documented site in Minnesota and good fine scale structure data was obtained. Analysis of the data was completed and the resulting velocity derivative spectra and statistics provided the essential high Reynolds number data required.

Based on all the data considered, "universal" Kolmogorov normalized spectra shapes as a function of turbulence Reynolds number were determined. The evolution of the spectral shapes with Reynolds number, the existence of inertial and/or dissipative local isotropy in the various flows, and the analytical solution to Lumley's model are discussed in detail in a paper entitled "The Fine Scale Structure of Turbulent Velocity Fields". The manuscript will be submitted to the Journal of Fluid Mechanics for publication.

An interesting result from our field experiment is the non-negligible contamination of some measured velocity and joint velocity-temperature statistics by the concomitant fluctuating temperature. An analysis of the temperature sensitivity of hot-wire and hot-film probes was carried out and corresponding data was obtained from the hot-wire calibrations from our field experiments as well as from a new calibration facility designed and constructed here. The facility allows precise control and measurement of both the calibration velocity and temperature. A short paper to present both the analysis and experimental results is in preparation.

## C. Flux Estimation Techniques in the Atmospheric Surface Layer

Further extension of the analysis of the Minnesota data to determine the validity of the direct dissipation and inertial dissipation techniques for estimating the turbulent fluxes of momentum, heat, and water vapor in the constant stress layer over land was carried out.

These two dissipation techniques are based on high frequency spectral measurements and normally provide good estimates of the fluxes, which are difficult to measure directly (via the direct covariance method). This demonstrates a technologically useful application of spectral measurements, which are normally of interest in basic turbulence or orderly structure research. Knowledge of the three turbulent fluxes is necessary to characterize the state of the atmospheric surface layer. Application of Monin-Obukhov similarity theory then provides detailed information on the structure of the turbulence in the surface layer. The turbulent fluctuations of velocity, temperature, and humidity are of importance to optical propagation and to aircraft approach problems.

The results of the Minnesota experiment on turbulent fluxes are presented in Champagne, Friehe, LaRue, and Wyngaard (1977) which will appear in the March 1977 issue of the Journal of the Atmospheric Sciences. The AFCRL-UCSD joint experiment provided a comparison of direct and indirect measurements of the surface layer fluxes of momentum, heat, and moisture under unstable conditions The direct momentum and heat flux measurements of the two groups agreed well, and also agreed well with values inferred by the direct dissipation technique. The moisture flux estimates from the inertial-dissipation technique also agreed well with directly-measured values.

Several of the important terms in the budgets of turbulent kinetic energy and turbulent scalar variances were evalulated directly. The imbalance (or pressure transport) term in the energy budget was estimated, and the ratio of the imbalance term to the dissipation term determined from the present experiment agrees well with the Kansas results. The production and dissipation rates of the humidity variance were found to be equal, while the dissipation rate of temperature variance exceeded its production rate, in contrast with previous results, implying an imbalanced temperature variance budget.

Several possible contributors to this imbalance are discussed.

The one-dimensional spectra of the temperature and streamwise velocity fluctuations are presented in Kolmogorov normalized form. Spectral moments to fourth order are shown to agree with other recent results. Values of the universal velocity and temperature spectral constants of $\alpha_1 = 0.52 \pm .02$ and $\beta_\theta = 0.46 \pm .02$ were obtained.

## D. The High Wavenumber Structure of Turbulent Temperature Fields

In the study of propagation of laser beams through the turbulent atmosphere, information regarding the atmospheric refractive-index fluctuations is essential. The single most important parameter providing that information is the refractive-index structure parameter $C_n^2$, which is a proportionality factor in the Kolmogorov 2/3 power law expression for the structure function. At optical wavelengths, it is usually assumed that refractive-index fluctuations are produced solely by fine scale temperature fluctuations in the atmosphere. The importance of temperature and humidity fluctuations on refractive-index fluctuations is discussed by Friehe, La Rue, Champagne, Gibson, and Dreyer (1975). The lack of data on high frequency temperature fluctuations in atmospheric or laboratory flows became apparent. An experimental study was initiated to provide the required information and to investigate the high wavenumber Kolmogorov normalized spectral shapes for universal behavior.

The fine scale temperature data from the Minnesota experiment proved valuable in the study. Further data was obtained from a large twelve inch diameter heated jet. A five hp vane-axial blower supplied air past 70 KW heaters and then through a 4:1 contraction to the nozzle.

This facility was mounted on an electrically driven hi-rise platform and elevated to 16 feet above the laboratory floor. The laboratory in this case was the largest we had available, the UCSD gymnasium. Good fine scale temperature data was obtained from the experiment. The importance of correcting the scalar spectra for effects caused by deviations from Taylor's approximation is being investigated. Appropriate correction equations for the scalar case have been derived and solved in conjunction with John Wyngaard of the NOAA wave propagation laboratory. It is planned to compare measured and corrected hot jet and Minnesota data with Gaussian and other theoretical spectral shapes. Also comparison with the low Reynolds number heated cylinder and grid wake data, currently being obtained by John La Rue of this laboratory, will be performed to determine if a universal scalar spectral shape valid for all sufficiently high Reynolds numbers exists.

## E. Relaminarization of Turbulent Pipe Flow

Transition from laminar to turbulent flow has been the object of considerable investigation both experimentally and theoretically for many years. The phenomenon of reverse transition or relaminarization has received attention only recently and the limited available evidence indicates distinct dissimilarities from the transition process -- for example lack of an abrupt turbulent-non-turbulent interface. As the initial state of the flow is turbulent, no analytical approach is yet feasible and experimental studies are necessary in order to understand the basic mechanism of the relaminarization process. Such knowledge is highly desirable if one hopes to control transition to and from turbulence.

Reverse transition in boundary layers undergoing a rapid acceleration through a strong favorable pressure gradient has been studied by many investigators. Relaminarization occurs also in initially fully developed turbulent pipe and other internal flows subjected to large decreases in

Reynolds number. Turbulence cannot seem to sustain itself in these flows below a certain critical Reynolds number which undoubtedly varies with the type of flow. Only a few preliminary studies of relaminarization of internal flows have been carried out. For the present investigation, I choose a basic turbulent flow field for which a maximum of experimental results and, as much as possible, a fundamental understanding of the structure of the initial flow field was available. Turbulent flow through a cylindrical pipe was selected and it is a flow of much technological interest. Also the study of reverse transition in a pipe will complement and extend the detailed work by Wygnanski and myself on transition in pipe flows.

An experimental facility was designed and constructed to allow careful expansion of an initially fully developed turbulent pipe flow to decrease the Reynolds number gradually by a factor of 5. This is accomplished by use of a $1^\circ$ half angle diffuser section with very smooth and distortion free walls. Construction of the diffuser was carried out by electro-plating copper onto a smoothly machined, removable aluminum mandrel with the inside dimensions of the diffuser section. The diffuser section was designed such that, as one integral unit, it includes several diameters of the upstream pipe, a gentle curvature to the $1^\circ$ half angle section then, at the downstream end, a gentle curvature back to a straight pipe section and finally two diameters of the downstream pipe. This design prevent any abrupt curvature changes which might disturb the sensitive inner region of the wall velocity profile and facilitates alignment of the upstream and downstream pipes with the diffuser section.

The facility consists of a flow source, a 0.10 inch diameter orifice, a cylindrical pipe of 0.20 inches i.d. and 24 inches in length to establish a fully developed initial pipe flow, the diffuser section where a 5:1 increase in diameter is achieved and then another pipe with a constant i.d. of 1.000 inch. Several one inch diameter pipe sections of

different lengths up to 49.5 inches have been constructed from stainless steel. To insure uniformity in pipe diameter, special hardened steel balls were forced through the pipe sections. The final ball has a diameter of 0.999 inches. The pipes were then gently honed to obtain a smooth finish. This straightening and smoothing technique proved to be too difficult for longer pipes so precision bore glass tubing was obtained to construct pipes longer than 49.5 inches. Separate 42 inch long sections of precision bore glass tubing with ends specially ground concentric to 0.001 inch to insure bore alignment, can be assembled together with precision bore connecting collars. The various sections of the facility are carefully aligned with height gauges and x-y graduated mechanical stages. A laser light source is used in the system alignment procedure. The flow rate is determined from the pressure drop along 20.0 cm of the small pipe, measured with a MKS Baratron pressure transducer system, and from a Fischer and Porter rotometer. Static pressure taps, 0.013 inches in diameter, are located along both the upstream pipe and the diffuser section.

The rather restricted pipe diameter sizes were chosen with two criteria in mind. One was to keep the downstream pipe large enough to obtain reasonable spatial resolution with conventional hot-wire probes. The other is to obtain sufficiently high velocities at the required low Reynolds numbers so that accurate hot-wire measurements are possible. With the present design, cross-sectional averaged velocities as low as 50 cm/sec have to be measured at the lowest Reynolds numbers considered. The heat transfer from hot wires is sensitive to both fluid velocity and temperature and at low velocities the sensitivity to mean temperature can be significant. This imposed the requirement of careful measurement and control of the air temperature during calibration and experimental runs.

The temperature of the air flow is measured using a Rosemount platinum resistance thermometer and d. c. bridge circuit. Control of the air temperature is carried out in the flow source, which is a modified TSI Model 1125 calibrator, supplied by the building high pressure air system. The air, after being filtered by two Wilkerson micro-filters, is passed through a heat exchanger, which is mounted in a constant temperature bath, and then through an electrical heater unit. The air is cooled below the desired (ambient laboratory) temperature in the heat exchanger and then heated in the resistance wire heater unit to the desired temperature. Control of the current to the heater unit is achieved by a feedback control system activated by the Rosemount platinum resistance thermometer mounted downstream of the heater and at the location where hot-wire measurements are being carried out. The desired temperature is dialed in or set on the controller unit and a digital panel meter is utilized to read out the air temperature to a resolution of $0.1^{\circ}C$. For hot-wire calibration, the flow source provides air through a two-way valve to another TSI Model 1125 calibrator. The feedback control circuit and heater unit are recent modifications of the original facility to permit rapid and precise control of the flow temperature.

The general goals of the study are to: (1) establish the minimum downstream Reynolds number for which the flow remains fully turbulent through the diffuser and in the constant area pipe downstream; (2) measure the development of the mean velocity field; (3) measure the decay rate of the turbulent velocity components and shear stress and their respective spectra and co-spectra at different downstream locations; (4) examine as many terms as possible of the turbulent kinetic energy budget at various phases of the reverse transition process; (5) explore the possibility of slightly heating the wall of the downstream pipe to monitor turbulent transport from the walls. If the bursting phenomena or eruptions near the wall cease in this case as they did in the highly accelerated flows, the constant stress region in the velocity profile

may disappear. If these bursts provide most of the momentum exchange between the wall and the outer regions of the flow and are necessary for maintenance of self-sustaining turbulent flow, then knowledge of when they cease may shed light into the mechanism of the reverse transition process. The actual details of detection will be similar to that used in recent experiments on a turbulent boundary layer over a heated wall at USC. Some preliminary work on the detection problem will be carried out before a final detection technique is chosen.

A considerable amount of data on the development of the mean velocity and streamwise turbulent intensity fields has been obtained. Radial profiles were taken for values of downstream positions, $x/d$, of 0, 4.5, 29.5, and 49.5 for Reynolds numbers based on the downstream mean flow field, of 600, 1040, 1955, 2200, and 2600. $d$ is the downstream pipe diameter and $a$ is its radius. The data was recorded on analog tape using an HP 3960 tape deck. The analog data was subsequently digitized and analyzed to determine mean velocities and turbulent intensities. Spectra of the streamwise fluctuations were determined for selected values of $r/a$, $x/d$, and Reynolds number to provide further information on the turbulent field.

The effect of Reynolds number on the initial development of the flow field has been determined. The velocity profiles at the exit plane of the diffuser, $x/d = 0$, are considerably less blunt than the velocity distribution in fully developed turbulent flow in a constant area pipe. This can be attributed to the relative retardation of the lower velocity wall region fluid by the action of the adverse pressure gradient in the diffuser. In fact for the $Re = 600$ case, incipient separation occurs whereas for the $Re = 1040$ case no sign of separation is apparent. At $x/d = 4.5$, none of the profiles exhibit any indications of separation and the $Re = 600$ flow field has recovered.

The rapid flattening of the initial profiles is a result of the presence of the favorable pressure gradient and the increased turbulent mixing caused by the highly turbulent character of the initial flow. The initial turbulence levels are considerably greater than that occurring in fully developed turbulent flow through a constant area pipe. With increasing $x/d$, the mean velocity profiles exhibit a more gradual change back towards a parabolic type profile with the exception of the $Re = 2600$ case. There the profiles remain far from parabolic as the flow field is developing towards a self-sustaining turbulent state, presumably that of fully developed turbulent pipe flow. The turbulence intensity decreases with $x/d$ for all the $Re < 2000$ cases, with the rate of decrease being more rapid near the wall and in the centerline region than in the intermediate region of the flow. For the $Re = 2600$ case the distributions appear to be approaching that of the fully developed $Re = 50,000$ flow, except in the vicinity of the wall. This is not unexpected as at the lower Reynolds number the viscous effects near the wall are magnified.

Currently the development of the streamwise turbulent intensity with $x/d$ for $x/d > 50$ and $Re > 2000$ is being investigated. Values of to about 150 are being used. This should prove interesting as, for the $Re = 2600$ case, the intensity increases with $x/d$ beyond $x/d = 30$, where it is already considerably greater than the fully developed $Re = 50,000$ pipe flow value. Evidence of the existence of puffs is present in this data and they may be the cause of the high intensity values. A preliminary waveform eduction program has been developed and used to detect puffs in the presence of the relatively high intensity turbulence. The puffs are difficult to detect because of the background turbulence but are definitely in the flow even though it is already turbulent. The program is currently being refined by Dr. I. Wygnanski at USC.

The effect of Reynolds number on the radial distribution of turbulent intensity and its centerline value for fully turbulent flow is being determined. Reynolds numbers in the range 2600 to 50,000 are being used. Measurements of the development of the mean velocity field are also being taken for $x/d > 50$ and for the entire Reynolds number range of interest. For $Re < 2000$, the approach to a parabolic profile is being obtained and the role of the parameter $x/d\ Re$ on the evolution of the parabolic profile will be considered.

## 2. Publications During Grant Period


1. Wygnanski, I. J. and F. H. Champagne, "On Slugs and Puffs in Transitional Pipe Flow", J. Fluid Mech. 59, pp 281-335, 1973.

2. Friehe, C. A., Gibson, C. H., Champagne, and J. C. LaRue, "Turbulence Measurements in the Marine Boundary Layer", Atmospheric Technology 7, pp 15-23, 1975.

3. Friehe, C. A., LaRue, J. C., Champagne, F. H., Gibson, C. H., and G. F. Dreyer, "Effects of Temperature and Humidity Fluctuations on the Optical Refractive Index in the Marine Boundary Layer", J. Optical Society of America 65, pp 1502-1511, 1975.

4. Champagne, F. H., Wygnanski, I. J., and Yih-Ho Pao, "On the Two-Dimensional Mixing Layer", J. Fluid Mech. 74, pp 209-250, 1976.

5. Champagne, F. H., Friehe, C. A., LaRue, J. C., and J. C. Wyngaard, "Flux Measurements, Flux Estimation Techniques and Fine Scale Turbulence Measurements in the Surface Layer Over Land", accepted for publication in March issue of the Journal of the Atmospheric Sciences.

6. Champagne, F. H., Wygnanski, I. J., and C. H. Gibson, "The Fine Scale Structure of Turbulent Velocity Fields", to be submitted to the Journal of Fluid Mechanics.

7. Champagne, F. H. and C. A. Friehe, "The Temperature Sensitivity of Hot-Wire Anemometers", to be submitted to the Physics of Fluids.

8. Wyngaard, J. C., Champagne, F. H., Friehe, C. A., and J. C. LaRue, "The Fine Scale Structure of Turbulent Temperature Fields", to be submitted to the Journal of Fluid Mechanics.

## 3. Abstracts and Presentations During Grant Period

1. Friehe, C.A., Champagne, F.H., and C.H. Gibson, "Measurements of Turbulent Fluxes Over the Open Ocean", presented at 1972 Amer. Phys. Soc. Fluid Dynamics Meeting at the University of Colorado, Boulder, Colorado, November 20-22, 1972. Bull. Amer. Phys. Soc., Series II, 17(11), 1972.

2. Champagne, F.H., "Universal Similarity of the Fine Scale Structure of Turbulent Velocity Fields", presented at 1973 Amer. Phys. Soc. Fluid Dynamics Meeting at Yale University, New Haven, Connecticut, November 19-21, 1973. Bull. Amer. Phys. Soc., Series II, 18(11), 1973.

3. Champagne, F.H., Friehe, C.A., and C.H. Gibson, "Turbulence Measurements in the Atmospheric Turbulent Boundary Layer Over the Open Ocean", presented at Atmospheric Boundary Layer Meeting, Mainz, Germany, October 10-11, 1973.

4. Champagne, F.H., "The Fine Scale Structure of the Turbulent Velocity Field", invited lecture presented at the University of Marseille, Institut de Mécanique Statistique de la Turbulence, September 20, 1974.

5. Champagne, F.H., Friehe, C.A., and J.C. LaRue, "Estimation Methods for the Turbulent Fluxes of Momentum, Heat, and Moisture in the Atmospheric Boundary Layer Over Land", presented at 1975 Amer. Phys. Soc. Fluid Dynamics Meeting at University of Maryland, College Park, Maryland, November 24-26, 1975. Bull. Amer. Phys. Soc., Series II, 20(11), 1975.

6. Champagne, F.H., Friehe, C.A., LaRue, J.C., Mestayer, P.G., and C.H. Gibson, "Boundary Layer Measurements from an Island and Aircraft during AMTEX II", presented at 1976 Conference on Ocean-Atmosphere Interactions of the American Meteorological Society, Seattle, Washington, March 30-April 2, 1976. Bull. Amer. Meteor. Soc. 57, p 152, 1976.